VOLUME 71, NUMBER 20

JOC Articles

SEPTEMBER 29, 2006

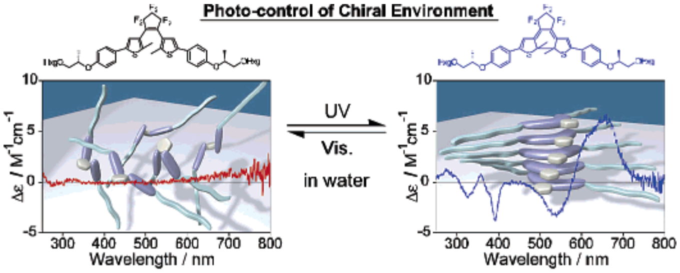
Self-Assembly of Photochromic Diarylethenes with Amphiphilic Side Chains: Reversible Thermal and Photochemical Control

Takashi Hirose,[†] Kenji Matsuda,*,[†,‡] and Masahiro Irie*,[†]

Department of Chemistry and Biochemistry, Graduate School of Engineering, Kyushu University and PRESTO, JST, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

irie@cstf.kyushu-u.ac.jp; kmatsuda@cstf.kyushu-u.ac.jp

Received March 8, 2006



Diarylethene derivatives with hexaethylene glycol side chains were synthesized and their self-assembling and photochromic reactivity were investigated. The diarylethenes showed photochromism in organic solvents and even in water. The aqueous solution of the compounds turned turbid quickly upon heating. The clouding behavior was investigated using ^{1}H NMR spectroscopy, dynamic light scattering, and absorption spectroscopy. It was revealed that, in the aqueous solution, the compounds self-assembled into aggregates, and the aggregates were loosened by raising the temperature. The cloud-point temperature of the closed-ring isomer was 5−7 °C lower than that of the open-ring isomer. When asymmetric methyl groups were introduced in the amphiphilic side chains, induced circular dichroism (ICD) was observed upon irradiation with UV light in water. This ICD was explained by the difference in the self-assembling behavior between the open- and the closed-ring isomers. It was suggested that the closed-ring isomers assembled into a chiral nanostructure.

Introduction

Hydrophobic interaction is the key driving force for the formation of three-dimensional structures of biopolymers and also is widely used for the construction of highly organized nanostructures in materials chemistry.[1] A poly(ethylene glycol) (PEG) side chain and an aromatic core are popular components for this strategy.[2] A flexible polar side chain and a rigid apolar core induce the formation of the stacked structure in polar solvents. When chiral PEG chains are used, chiral nanostructures can be formed.[3] Furthermore, the introduction of such polar side chains makes it possible for hydrophobic compounds to dissolve into water.[4] Solubility in water is a very important property to be applied to a biological field such as biosensors or drug deliveries.

[†] Kyushu University.

[‡] PRESTO, JST.

[1] (a) Hill, D. J.; Mio, M. J.; Prince, R. B.; Hughes, T. S.; Moore, J. S. *Chem. Rev.* **2001**, *101*, 3893−4012. (b) Nelson, J. C.; Saven, J. G.; Moore, J. S.; Wolynes, P. G. *Science* **1997**, *277*, 1793−1796. (c) Hirschberg, J. H. K. K.; Brunsveld, L.; Ramzi, A.; Vekemans, J. A. J. M.; Sijbesma, R. P.; Meijer, E. W. *Nature* **2000**, *407*, 167−170.

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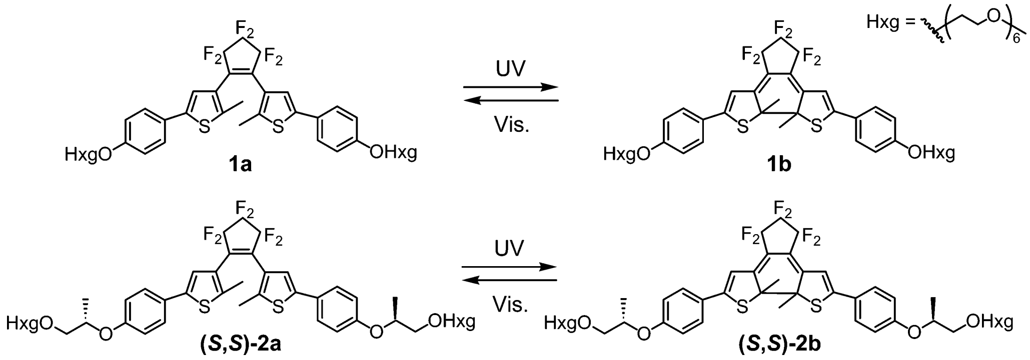
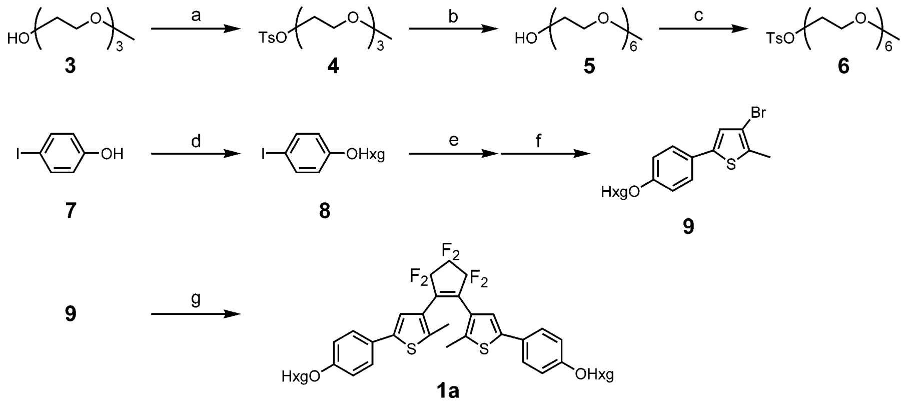
10.1021/jo060505t CCC: $33.50 © 2006 American Chemical Society
Published on Web 05/16/2006

SCHEME 1. Photochromism of Diarylethene with PEG Side Chains



SCHEME 2. Synthesis of Compound 1a[a]



[a] Reagents and conditions: (a) TsCl, aq NaOH, THF, 95%; (b) $HO(CH_2CH_2O)_3H$, aq KOH, 90%; (c) TsCl, aq NaOH, THF, 72%; (d) **6**, K_2CO_3, DMF, quantitative; (e) *n*-BuLi, dry THF, and then $(BuO)_3B$; (f) 2,5-dibromo-3-methylthiophene, aq Na_2CO_3, and then $Pd(PPh_3)_4$, 70% in two steps; (g) *n*-BuLi, dry THF, and then perfluorocyclopentene, 21%.

Diarylethenes are photochromic compounds that are potentially applicable to optical memory media because of the thermally stable and the fatigue-resistant properties.[5] Chiroptical property is of particular interest because the property can be used for a nondestructive readout.[6] The photochemical conrotatory cyclization of the diarylethene produces two enantiomeric closed-ring isomers ((*R*,*R*)- and (*S*,*S*)-) originating from two asymmetric carbon atoms. The stereoselective cyclization in a chiral environment has been accomplished in solution and in the single-crystalline phase.[7]

The stereoselective cyclization is not an exclusive strategy for the photoswitching of the chiroptical properties. Reversible formation of chiral structures along with photochromism can bring about the switching of chiroptical properties. The control of the self-assembled structures by using various types of photochromic compounds has been reported. Azobenzene is a very convenient photoactive molecule to control the self-assembled structures because it has a large conformational change along with its cis–trans isomerization.[8] Feringa et al. reported the design of the photoresponsive self-assembling system by using photochromic diarylethene derivatives.[7a] The difference in the preference of the helical structures between the open- and the closed-isomers controls the structure of the gel states. In a diarylethene system, the open-ring isomer has a relatively loose twisted conformation, whereas the closed-ring isomer has a stiff planar structure. Although the geometrical structure change of diarylethene is relatively small, the difference in rigidity and π conjugation associated with photochromism is anticipated to induce the change in the formation/dissociation of the self-assembled structures.

In this study, we synthesized diarylethenes having PEG side chains and investigated their photochromic property and self-

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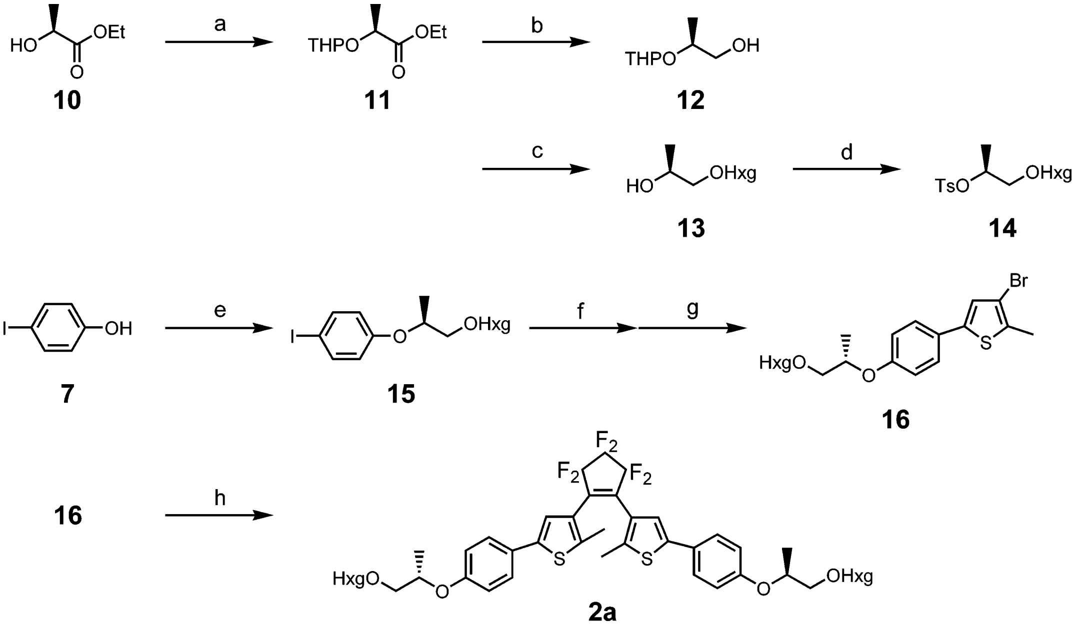
SCHEME 3. Synthesis of Compound (*S*,*S*)-2a[a]



[a] Reagents and conditions: (a) 3,4-dihydro-2*H*-pyran, PPTS, dry CH_2Cl_2, quantitative; (b) $LiAlH_4$, Et_2O, 91%; (c) **6**, dry THF, and then PPTS, EtOH, 78%; (d) TsCl, aq NaOH, THF, 75%; (e) **14**, K_2CO_3, DMF, 57%; (f) *n*-BuLi, dry THF, and then $(BuO)_3B$; (g) 2,4-dibromo-3-methylthiophene, aq Na_2CO_3, and then $Pd(PPh_3)_4$, 40% in two steps; (h) *n*-BuLi, dry THF, and then perfluorocyclopentene, 20%.

assembling behavior. The application to the reversible CD and ORD signal switching has also been examined.

Results and Discussion

Synthesis. As described before, to employ the hydrophobic interaction for the self-assembly, the molecule is required to have amphiphilic side chains and an aromatic core. For the flexible amphiphilic side chains, a hexaethylene glycol (Hxg) group was adopted because of the facile preparation and the solubility in many solvents, including water.[4] For the aromatic photochromic core, 1,2-bis(2-methyl-5-phenyl-3-thienyl)perfluorocyclopentene was selected because of the established photochromic performance. In this manner, amphiphilic diarylethene **1a** was designed. Chiral sources were introduced in **(*S*,*S*)-2a** to probe the chiroptical properties (Scheme 1). Compounds **1a** and **(*S*,*S*)-2a** were synthesized according to Schemes 2 and 3. Tosyl-protected Hxg side chain **6** was synthesized according to the literature.[4] To introduce asymmetric methyl groups as chiral sources nearby the aromatic core, (*S*)-ethyl lactate was protected by tetrahydropyranyl group, reduced by $LiAlH_4$, and then reacted with tosyl-protected Hxg chain **6** to give chiral side chain **14**. Bromothiophene derivatives **9** and **16** were synthesized by Suzuki coupling of 2,4-dibromo-5-methylthiophene with phenyl boronic acid derivatives having a PEG chain. To obtain compounds **1a** and **(*S*,*S*)-2a**, the bromothiophene derivatives were lithiated and reacted with a perfluorocyclopentene. The structures of **1a** and **(*S*,*S*)-2a** were confirmed by NMR, MASS spectroscopy, and elemental analysis.

Photochromic Reactions. The photochromic reactivity of diarylethenes **1** and **(*S*,*S*)-2** was studied in water, ethyl acetate, and hexane solution (Figure 1). Compounds **1** and **(*S*,*S*)-2** show an excellent photochromic performance in organic solvent and even in water. Under irradiation with 313-nm light, the colorless open-ring isomers **1a** and **(*S*,*S*)-2a** turned blue, and the blue color disappeared upon irradiation with 578-nm light. The blue color is due to the photogenerated closed-ring isomers **1b** and **(*S*,*S*)-2b**. The closed-ring isomers were isolated using reversed-phase HPLC. The conversion ratios under irradiation with 313-nm light, which were determined by comparing the spectra of the isolated closed-ring isomer **1b** with that in the photostationary state, were 90.9, 99.0, and 97.6% in water, ethyl acetate, and hexane, respectively. The spectroscopic properties were summarized in Table 1. In aqueous solution, the absorption spectra showed a structured absorption band, and the conversion ratio was lower than that in ethyl acetate. Furthermore, absorption maxima are blue-shifted in water. The spectral shape and conversion ratio in hexane are similar to that in ethyl acetate. The unique behavior in water implied the formation of aggregates of compounds **1** and **(*S*,*S*)-2**. The cyclization and the cycloreversion quantum yields of compound **1** in water were 0.48 (313 nm) and 3.3×10^{-3} (517 nm), respectively.

Clouding Behavior. Upon heating, the aqueous solutions of compound **1a** and **(*S*,*S*)-2a** turned turbid[9] at 40−50 °C (Figure 2). The turbid solutions returned to clear solutions upon cooling

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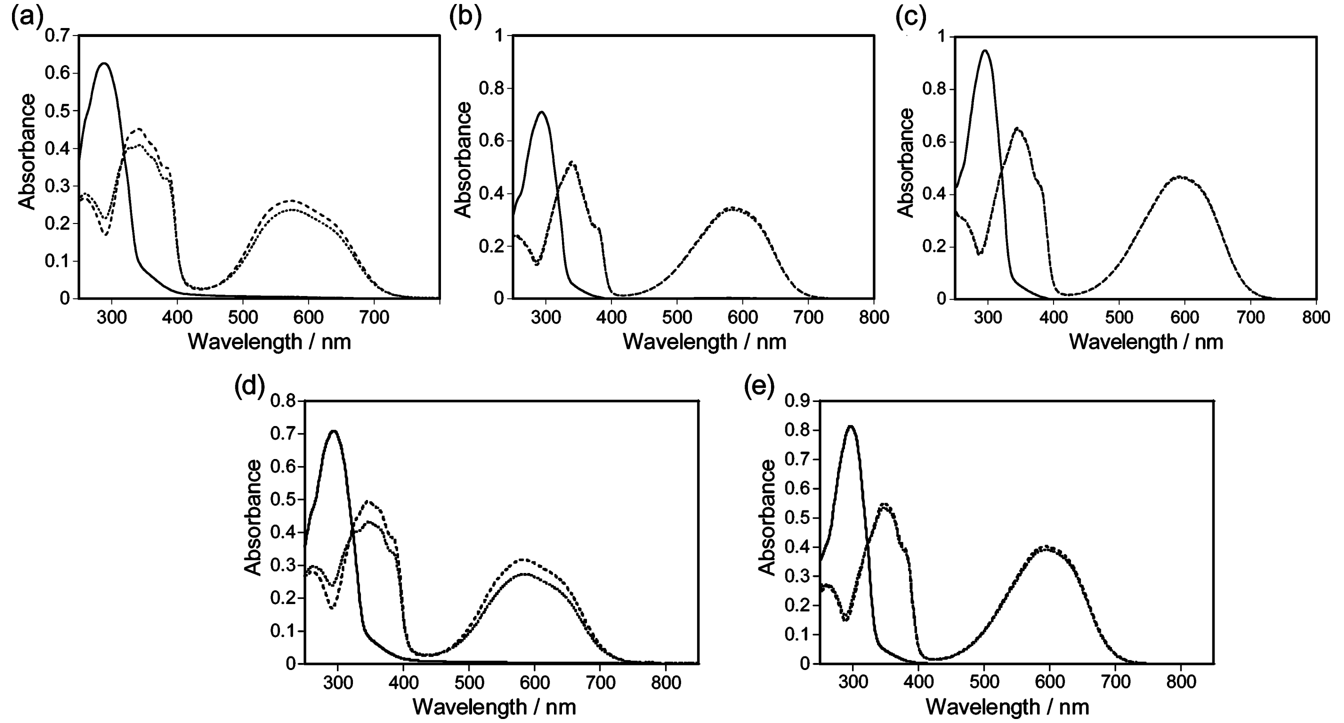

FIGURE 1. Absorption spectra of diarylethenes along with photochromism: (a) **1** in water (2.2×10^{-5} M); (b) **1** in hexane (1.6×10^{-5} M); (c) **1** in ethyl acetate (2.0×10^{-5} M); (d) ***(S,S)*-2** in water (2.0×10^{-5} M); (e) ***(S,S)*-2** in ethyl acetate (1.6×10^{-5} M). Solid line denotes the open-ring isomer, dashed line denotes the closed-ring isomer, and dotted line denotes the sample in the photostationary state under irradiation with 313-nm light.

TABLE 1. Absorption Maxima of the Open- and the Closed-Ring Isomers and the Conversion from the Open- to Closed-Ring Isomers under Irradiation with 313-nm Light

compound	1			(*S*,*S*)-2	
solvent	water	ethyl acetate	hexane	water	ethyl acetate
open-ring isomer $\lambda_{\max}$ (ϵ; nm)	289 (2.8×10^4)	296 (4.8×10^4)	294 (4.5×10^4)	294 (3.5×10^4)	297 (5.0×10^4)
closed-ring isomer $\lambda_{\max}$ (ϵ; nm)	573 (7.9×10^3)	592 (2.4×10^4)	583 (2.2×10^4)	583 (1.6×10^4)	594 (2.5×10^4)
conversion (%)	90.9	99.0	97.6	86.1	97.2

to room temperature. This clouding behavior is thermally reversible and sensitive to temperature change.

The cloud-point temperature of the solutions was determined for the open-ring isomer and the sample in the photostationary state under irradiation with 313-nm light by monitoring the change of the absorbance at 800 nm, where the diarylethene chromophore has no absorption. Figure 3 shows the absorption spectral changes upon heating and the plot of the absorbance at 800 nm against temperature for compound **1**. At higher temperatures, both absorption bands in the ultraviolet and the visible region were red-shifted and sharpened. This behavior suggests the collapse of aggregate upon heating. The spectral change occurred in a narrow temperature range. The aqueous solution of the open-ring isomer **1a** turned turbid at 47−48.5 °C, while the photostationary-state solution changed at 40−42 °C. Thus, the cloud-point temperature is dependent on the configuration of the diarylethene units, open- or closed-forms. The temperature was lowered by about 5−7 °C upon UV irradiation.

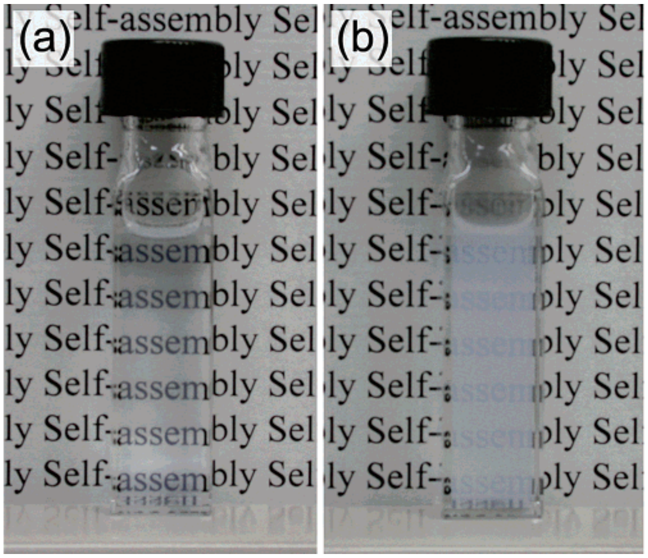

FIGURE 2. Photographs of the H_2O solution of compound **1a** (a) at room temperature and (b) at 60 °C.

To investigate the molecular motion in the aggregate, a variable-temperature ^{1}H NMR measurement was carried out. At room temperature, broadened peaks were observed in D_2O,

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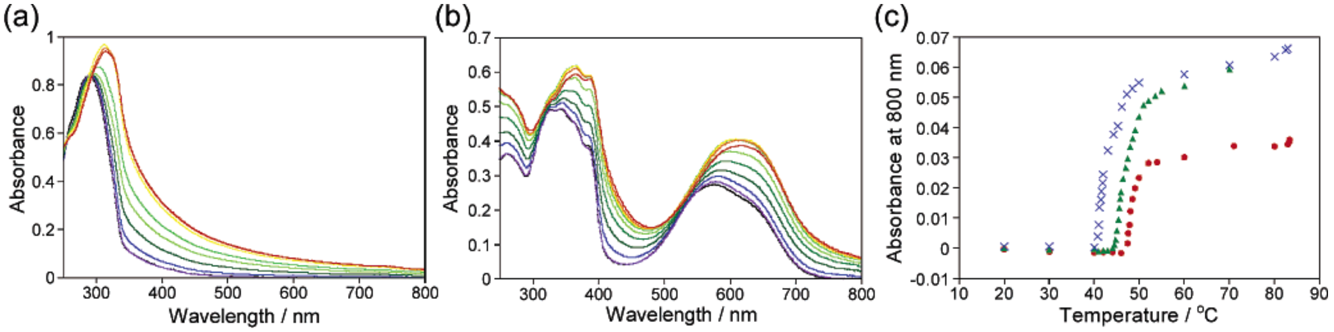

FIGURE 3. Absorption spectral changes of an aqueous solution of compound **1** upon heating. (a) The open-ring isomer (3.0×10^{-5} M) measured at 20, 46, 47.4, 47.8, 48.5, 50, 60, 70, and 80 °C from bottom to top; (b) the sample in the photostationary state under irradiation with 313-nm light (2.8×10^{-5} M) measured at 20, 40, 41, 42, 44.2, 46.2, 50, 60, 70, and 80 °C from bottom to top; (c) the plot of absorbance at 800 nm against temperature. The open-ring isomer (circle plot), the sample at the conversion ratio of 50% (delta plot), and the sample in the photostationary state under irradiation with 313-nm light (crisscross plot).

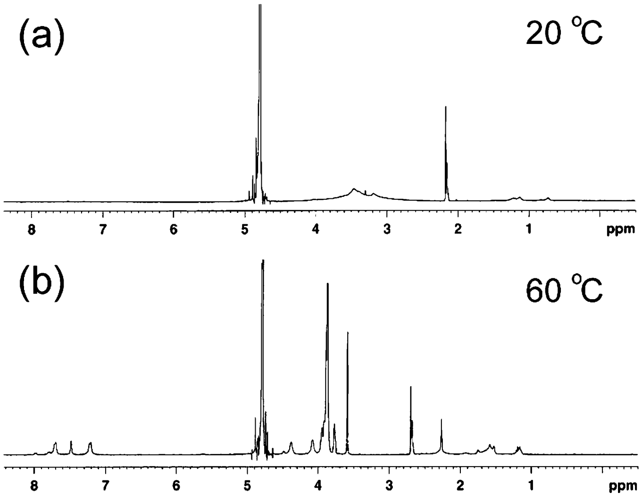

FIGURE 4. Variable-temperature ^{1}H NMR spectra of compound **1a** in D_2O (a) at 20 °C and (b) at 60 °C.

while corresponding peaks in $CDCl_3$ were sharp. When the D_2O solution was heated, the broadened peaks turned sharp. The peaks appeared at about 3.5−4.5 ppm and at about 7.0−8.0 ppm and were assignable to the protons of the Hxg side chain and the diarylethene core, respectively (Figure 4). It should be noted that the compounds in the D_2O solution at high temperature showed sharp peaks even though the solution was turbid. This result indicates that the aggregated structures formed at low temperature were collapsed upon heating, and the collapsed loosened structures should cause the light scattering.

Dynamic Light Scattering (DLS) and Atomic Force Microscopy (AFM) Measurements. To examine the size distribution of the aggregates of compounds **1** and ***(S,S)*-2**, DLS measurements were carried out (Figure 5). The peak corresponding to the size of around 100 nm was observed in water. However, in ethyl acetate, the light scattering signal was too weak to obtain the size distribution. Both the diarylethene core and the PEG side chains are soluble in ethyl acetate. Therefore, compounds **1** and ***(S,S)*-2** should be molecularly dispersed in ethyl acetate. The peak in water at room-temperature turned sharp when the solution was heated. The transition temperature was 45−50 °C for the open-ring isomer **1a** and 42−46 °C for the photostationary-state sample. The observed transition temperature agreed well with the temperature obtained by ^{1}H NMR and UV−vis absorption spectra.[10]

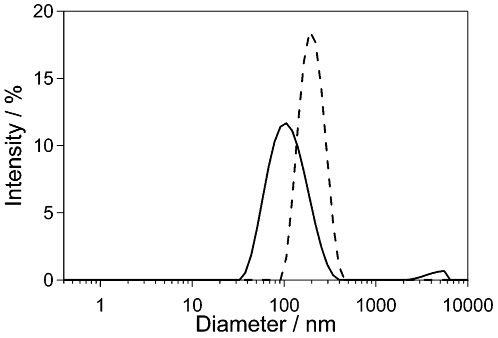

FIGURE 5. The size distribution of the open-ring isomer **1a** in water (2×10^{-5} M) at 30 °C (solid line) and heated to 70 °C (dashed line).

To obtain supporting information about the aggregated structure, AFM measurements were performed (Figure 6). The observed heights of the aggregates were 30−50 nm. Considering that these aggregations were measured in the absence of solvent, the observed size is substantially compatible with DLS measurements.

Switching of the CD and ORD Spectra. A CD spectral measurement is the most convenient way to detect chiral structural change, because the spectrum reflects supramolecular structures very sensitively. CD spectral changes along with photochromism were measured for compound ***(S,S)*-2** in water and in ethyl acetate. No CD signal was observed before and after the photocyclization reaction in ethyl acetate, where ***(S,S)*-2** is molecularly dispersed. In water, the colorless open-ring isomer ***(S,S)*-2a** did not show any CD signal, while intense CD signal was observed upon UV irradiation (Figure 7). To know the origin of the CD signal, diastereomeric excess (de) of the photoproduct was measured using analytical HPLC, but de was not discerned in the product.[11] This indicates that the CD signal is not due to the stereoselective cyclization. The CD signal of ***(S,S)*-2b** in water corresponding to the absorption band of the closed-ring isomer in the visible region shows an exciton-splitting type with a positive first Cotton effect around 670 nm and a negative second Cotton effect around 530 nm. The observed CD signal is due to the intermolecular torsion of the transition moments in the visible absorption band. It is known

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[10] Though the change of the size distribution associated with photoirradiation was measured for the compound ***(S,S)*-2**, no significant change was perceived. See Supporting Information.

[11] See Supporting Information.

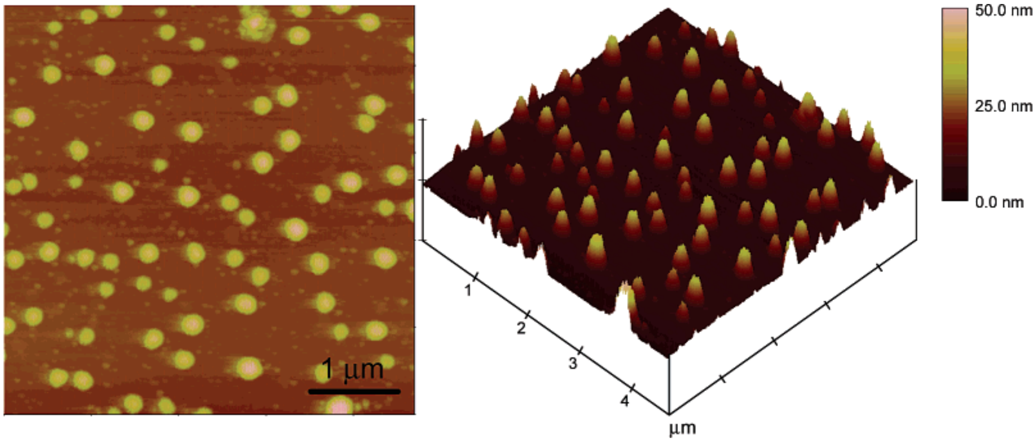

FIGURE 6. Tapping mode AFM image of the open-ring isomer **1a** on mica in the absence of solvent.

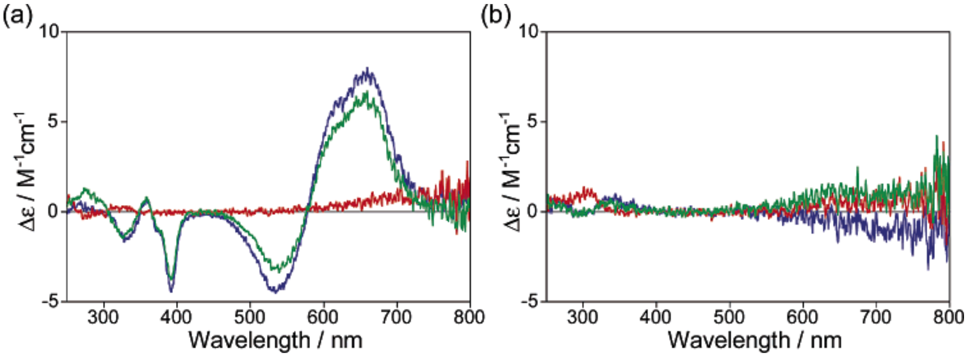

FIGURE 7. CD spectra of **(*S*,*S*)-2** (a) in water (2.6 × 10^{-5}) and (b) in ethyl acetate (1.6 × 10^{-5}). Red line, the open-ring isomer; blue line, the closed-ring isomer; green line, the sample in the photostationary state under irradiation with 313-nm light.

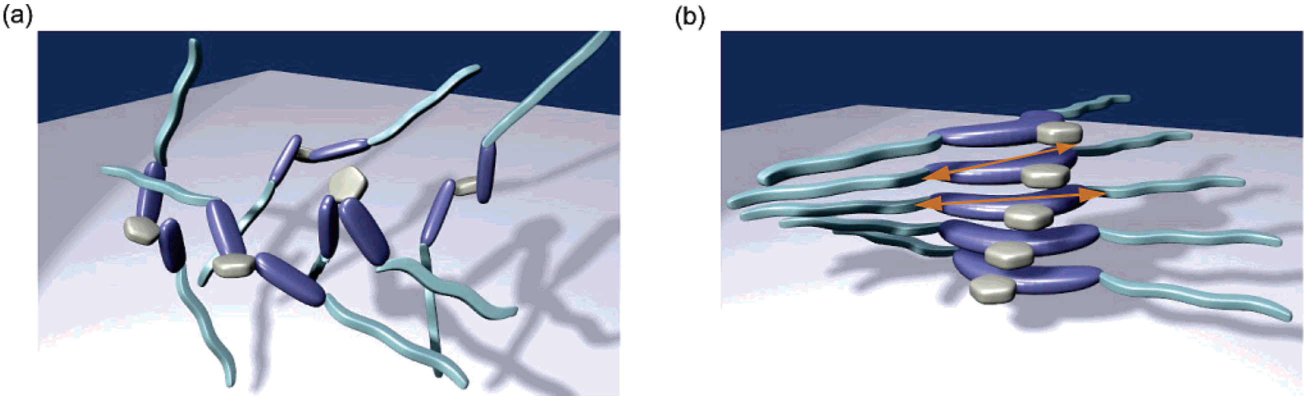

FIGURE 8. Model of the self-assembled nanostructure of **(*S*,*S*)-2** in water. (a) A nanostructure of the open-ring isomer and (b) that of the closed-ring isomer. Only the nanostructure composed of the closed-ring isomers has a chiral property. The orange arrows show the torsion of the transition moments along the long axis of the diarylethene chromophore.

that the transition moment of the closed-ring isomer of a diarylethene exists along the long axis of the molecule.[12] The self-assembled structure model that explains the results is shown in Figure 8. In this figure, the hydrophobic diarylethene moiety is stacked with torsion of their transition moment and surrounded by an amphiphilic PEG side chain. Thus, these CD spectral changes indicate that the nanostructure of the photogenerated **(*S*,*S*)-2b** in water has a chiral environment and that the nanostructural chirality can be switched upon photoirradiation.

The induced CD signal intensity depends on the twist sense bias of the transition moment and the distance between the two chromophores. The twist sense bias and the distance are expected to depend on the interaction between the chromophores, which regulate the relative conformation of the chromophores. The closed-ring isomer has a planar structure so that the stacked structure is favorably formed by the solvophobic effect. On the other hand, the open-ring isomers have a bulky twisted conformation, which prevents the formation of the stacked structure. The difference is considered to cause the different CD spectra between the open- and closed-ring isomers.

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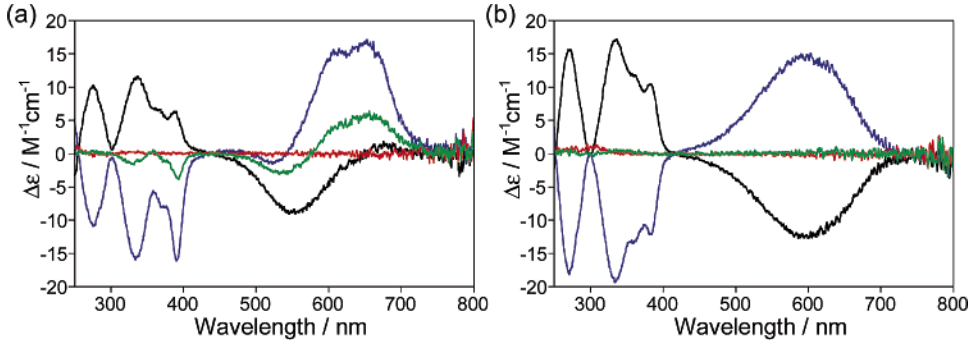

FIGURE 9. CD spectra of **(*S*,*S*)-2** after separating the diastereomers (a) in water (2.6×10^{-5}) and (b) in ethyl acetate (1.4×10^{-5}). Red line, the open-ring isomer; blue line, the closed-ring isomer; green line, the sample in the photostationary state under irradiation with 313-nm light; black line, the closed-ring isomer of the other diastereomer.

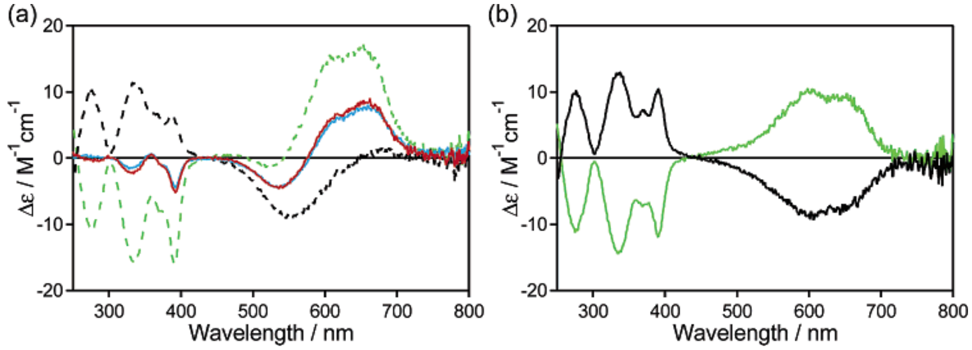

FIGURE 10. CD spectra of **(*S*,*S*)-2** in water and the calculated spectra. (a) Green dashed line [A], original CD spectrum of a diastereomer (the blue line in Figure 9a); black dashed line [B], original CD spectrum of the other diastereomer (the black line in Figure 9a); red solid line [C], the calculated spectrum by averaging A and B; light blue solid line [D], original spectrum of the racemic closed-ring isomer (the blue line in Figure 7a). (b) Calculated CD spectra *in water* corresponding to Figure 9b. Green solid line, the calculated spectrum by subtracting D from A; black solid line, subtracting D from B.

To investigate the effect of the chiral source at the reactive carbon, two diastereomers, **(*S*,*S*,*S*,*S*)-2b** and **(*S*,*R*,*R*,*S*)-2b**, were separated by chiral HPLC, and the CD spectra were measured as shown in Figure 9. Figure 9b shows the results in ethyl acetate. The separated diastereomers showed strong CD signals without exciton coupling. The CD spectra were similar to those reported for the enantiomerically separated closed-ring isomers of the diarylethenes.[7] The diastereomers showed signals with the same intensity and opposite signs. After irradiation with visible light, the CD signals disappeared, and successive irradiation with UV light did not regenerate the CD signals. This result is consistent with the fact that stereoselective cyclization does not take place, and compound **(*S*,*S*)-2** is molecularly dispersed in ethyl acetate. Thus, the CD signal originating from asymmetric carbon atoms at the reactive center observed in ethyl acetate does not have exciton splitting.

Figure 9a shows the spectra in water. In this case, the spectra of the two diastereomers were not mirror images. Upon irradiation with visible light, the CD signals of each diastereomer disappeared in a similar manner as in ethyl acetate. Successive irradiation with UV light gave the exciton-coupled CD signal identical with that observed before separation of the diastereomers. Regardless of the starting diastereomers, **(*S*,*S*,*S*,*S*)-2b** and **(*S*,*R*,*R*,*S*)-2b**, the regenerated spectra were identical, suggesting the racemization took place when the sample was converted to the open-ring isomer.

The CD signals originating from the chirality of the reactive center, which has no exciton splitting, should have the same intensity and opposite signs even in water, so that these components should have canceled out each other when the spectra was added together. Interestingly, calculated averaged spectrum (spectrum C in Figure 10a: [A + B]/2, where A is the green dashed line, and B is the black dashed line) reproduced the exciton-splitting shape of the observed spectrum before separation of diastereomers in water (spectrum D in Figure 10a). Furthermore, a pair of CD signals with the same intensity and opposite signs were obtained when subtracting spectrum D from each original spectra A and B (Figure 10b). The subtraction enables the exclusion of the effect of the exciton-coupled signal that was always observed in aqueous solution as a result of the assembled structure. The resulting signals with mirror symmetry are ascribed to the genuine component of the reactive-center chirality in the spectra of **(*S*,*S*)-2b** measured *in water*.

These facts support that the CD spectra of the diastereomer in water consist of two different components: one is an exciton-coupled CD signal originating from a chiral environment of the self-assembled nanostructure; the other is a signal without exciton splitting originating from asymmetric carbon atoms at the reactive center.

In general, photochromic reactions have no light-intensity threshold. Even very weak light can induce the reaction. Therefore, when used in optical memory, the memory is destroyed during readout with weak reading light. The destructive readout can be avoided by using optical rotation as a detection signal, because the refractive index change can be read with light longer than the absorption band. To evaluate the possibility of a nondestructive readout, ORD spectral change was measured for compound **(*S*,*S*)-2** in water (Figure 11). The

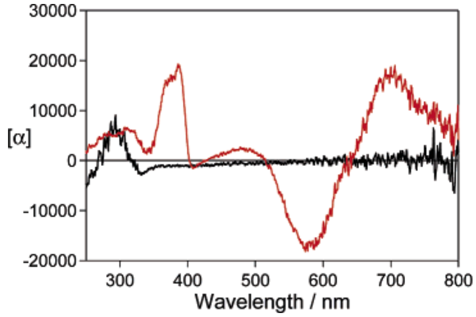

FIGURE 11. ORD spectra of **(*S*,*S*)-2** in water (6.6 × 10^{-5} M). The black line denotes the open-ring isomer, and the red line denotes the sample in the photostationary state under irradiation with 313-nm light.

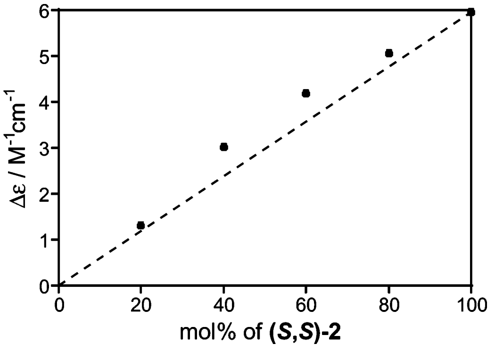

FIGURE 12. The plot of molar ellipticity at 670 nm against the mole percentage of **(*S*,*S*)-2**.

change of ORD intensity was observed even at 800 nm, where the closed-ring isomer of the diarylethene chromophore has no absorption, and the change was completely reversible by photoirradiation. This result indicates that a nondestructive readout is possible by the detection of optical rotation using the light of long wavelength, which does not induce the photochromic reaction.

"Sergeants and Soldiers" Character. The above results indicate that **(*S*,*S*)-2b** self-assembled into chiral nanostructures in aqueous solution. To know the mechanism of the chiral induction, CD spectra were measured for the mixture of achiral **1** and chiral **(*S*,*S*)-2**. This experiment is the so-called "Sergeants and Soldiers"[3b,13] experiment. If compounds **1** and **(*S*,*S*)-2** aggregate independently, an equimolar mixture solution should show a half intensity of the CD signal. On the other hand, if compound **(*S*,*S*)-2** assembles into a chiral structure with achiral compound **1**, it is possible that a small amount of optically active substance can give the chiral environment to the allover system.

Open-ring isomers **1a** and **(*S*,*S*)-2a** were dissolved in water, and a CD spectrum was measured in the photostationary state under irradiation with 313-nm light. Figure 12 shows the plot of molar ellipticity at maximum wavelength in the visible region against the mole percentage of **(*S*,*S*)-2**. Although the molar ellipticity tends to deviate from the linear relationship, the effect is very weak. The weak effect implied that the intermolecular interaction between **1** and **(*S*,*S*)-2** is insignificant.

As described before, in the photocyclization reaction, no diastereoselection was observed. This also suggests that the intermolecular interaction is weak. When the intermolecular interaction is strong, the conformation of the open-ring isomer would be restricted to (*P*)-helix or (*M*)-helix, which would lead to stereoselective cyclization. In turn, the stable aggregates, which are formed by strong intermolecular interactions, would have less sensitivity to external stimuli, such as light or temperature.

Conclusions. In this study, we have synthesized diarylethene derivatives with Hxg side chains as an amphiphilic group and investigated their photochromic properties and self-assembling behavior. The compounds **1** and **(*S*,*S*)-2** were molecularly dispersed in common organic solvents such as ethyl acetate, however, they self-assembled into nanostructures in water. The aqueous solution turned turbid in a narrow temperature range upon heating, and the cloud-point temperature is dependent on the configuration of the diarylethene units, open- or closed-forms. The temperature decreased as much as 5−7 °C upon UV irradiation. When an asymmetric methyl group was introduced nearby the aromatic core, induced circular dichroism (ICD) was observed for the closed-ring isomer. Though both isomers form the self-assembled nanostructures around 100 nm, only the closed-ring isomer has a chiral environment. The chiral environmental change between the open- and the closed-ring isomers enables reversible photocontrol of the ICD by irradiation with the appropriate light. This concept gives us a new strategy for the photoswitching of the chiroptical properties. Although the solid-state system is ideal, the results reported here can be a new candidate for the nondestructive readout method without stereoselective cyclization.

Experimental Section

A. Materials. Compounds **4**, **5**, and **6** were prepared according to the method reported previously.[4] Triethylene glycol monomethyl ether (**3**), *p*-iodophenol (**7**), and ethyl lactate (**10**) were purchased from commercial sources. Compound **12** was prepared from compound **10** via compound **11**, according to the literature.[14]

***p*-Iodo-{2-[2-(2-{2-[2-(2-methoxyethoxy)ethoxy]ethoxy}ethoxy)ethoxy]ethoxy}benzene (8).** Hxg monomethyl ether **6** (6.00 g, 13.3 mmol) and *p*-iodophenol **7** (0.504 g, 4.0 mmol) were added to a solution of K_2CO_3 (5.5 g, 40 mmol) in DMF (40 mL). The solution was stirred for 7 h at 70 °C. After cooling, the mixture was poured into aqueous HCl (pH = 2, 200 mL) and extracted with CH_2Cl_2 (100 mL × 2). The organic layer was washed with water (100 mL × 3) and brine (100 mL × 1) and dried over magnesium sulfate, and the solvent was evaporated in vacuo. The crude product was purified by silica gel column chromatography (ethyl acetate) to yield **8** (2.04 g, 4.09 mmol, quantitatively) as a viscous colorless oil. ^{1}H NMR ($CDCl_3$, TMS, 200 MHz) δ 3.38 (s, 3H, Me), 3.50−4.20 (m, 24H), 6.70 (d, $J = 9$ Hz, 2H, Ar), 7.54 (d, $J = 9$ Hz, 2H, Ar); FAB HRMS (*m*/*z*) $[M]^+$ calcd for $C_{19}H_{31}IO_7$, 498.1115; found, 498.1138.

3-Bromo-5-(4-{2-[2-(2-{2-[2-(2-methoxyethoxy)ethoxy]ethoxy}ethoxy)ethoxy]ethoxy}phenyl)2-methylthiophene (9). To a solution of compound **8** (300 mg, 0.602 mmol) in dry THF (10 mL) was slowly added *n*-butyllithium (BuLi) hexane solution (1.6 M, 0.395 mL, 0.632 mmol) at −78 °C under an argon atomosphere. The solution was stirred for 1 h at −78 °C. After the addition of boric acid tri-*n*-butyl ester (0.242 mL, 0.903 mmol), the reaction mixture was further stirred for 1 h. The reaction was stopped by the addition of water. 2,4-Dibromo-5-methylthiophene (231 mg,

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(13) (a) van Gestel, J.; Palmans, A. R. A.; Titulaer, B.; Vekemans, J. A. J. M.; Meijer, E. W. *J. Am Chem. Soc.* **2005**, *127*, 5490−5494. (b) Wilson, A. J.; Masuda, M.; Sijbesma, R. P.; Meijer, E. W. *Angew. Chem., Int. Ed.* **2005**, *44*, 2275−2279. (c) Brunsveld, L.; Schenning, A. P. H. J.; Broeren, M. A. C.; Janssen, H. M.; Vekemans, J. A. J. M.; Meijer, E. W. *Chem. Lett.* **2000**, 292−293.

(14) Chiellini, E.; Galli, G.; Carrozzino, S. *Macromolecules* **1990**, *23*, 2106−2112.

0.903 mmol), $Pd(PPh_3)_4$ (34.8 mg, 0.030 mmol), and aqueous Na_2CO_3 (20 w %, 10 mL) were added to the solution. The solution was refluxed for 16 h. The reaction product was extracted with ethyl acetate (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, filtered, and evaporated. The crude product was purified by silica gel column chromatography (ethyl acetate) to yield **9** (230 mg, 0.42 mmol, 69.8%) as a yellow oil. ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 2.40 (s, 3H, Me), 3.38 (s, 3H, Me), 3.52−4.20 (m, 24H), 6.91 (d, $J = 9$ Hz, 2H, Ar), 6.98 (s, 1H), 7.42 (d, $J = 9$ Hz, 2H, Ar); FAB HRMS (*m/z*) $[M]^+$ calcd for $C_{24}H_{35}BrO_7S$, 546.1287; found, 546.1284.

1,2-Bis[5-(4-{2-[2-(2-{2-[2-(2-methoxyethoxy)ethoxy]ethoxy}-ethoxy)ethoxy]ethoxy}phenyl)2-methylthiophene-3-yl]perfluorocyclopentene (1). To a solution of compound **9** (383 mg, 0.678 mmol) in dry THF (5 mL) was slowly added *n*-butyllithium (BuLi) hexane solution (1.6 M, 0.461 mL, 0.737 mmol) at −78 °C under an argon atomosphere. The solution was stirred for 1 h at −78 °C. After the addition of perfluorocyclopentene (0.042 mL, 0.302 mmol), the reaction mixture was further stirred for 1 h at that temperature. The reaction was stopped by the addition of water. The reaction product was extracted with ethyl acetate (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, filtered, and evaporated. The crude product was purified by silica gel column chromatography (ethyl acetate/acetone = 1:1) to yield **1** (70 mg, 0.063 mmol, 20.9%) as a blue oil. ^1H NMR ($CDCl_3$, TMS, 400 MHz) δ 1.94 (s, 6H, Me), 3.37 (s, 6H, Me), 3.52−3.76 (m, 40H), 3.84−3.90 (m, 4H), 4.12−4.18 (m, 4H), 6.93 (d, $J = 9$ Hz, 4H, Ar), 7.16 (s, 2H), 7.45 (d, $J = 9$ Hz, 4H, Ar). FAB MS (*m/z*) $[M]^+$ 1108.83. Anal. Calcd for $C_{53}H_{70}F_6O_{14}S_2$: C, 57.39; H, 6.36. Found: C, 57.19; H, 6.34. UV−vis (H_2O) λ_{max} (ϵ) 289 (28 000); (AcOEt) λ_{max} (ϵ) 296 (48 000); (hexane) λ_{max} (ϵ) 294 (45 000).

(*S*)-1-{2-[2-(2-{2-[2-(2-Methoxy-ethoxy)-ethoxy]-ethoxy}-ethoxy)-ethoxy]-ethoxy}-propan-2-ol (13). To a solution of (*S*)-2-(tetrahydropyran-2-yloxy)-propan-1-ol **12** (3.02 g, 18.7 mmol) and *p*-toluenesulfonic acid Hxg monomethyl ether (12.8 g, 21.1 mmol) in dry THF (100 mL) was added NaH (1.27 g, 52.9 mmol). The solution was refluxed for 12 h. After cooling, the reaction was quenched by the addition of water, and the solution was evaporated to remove THF. The reaction product was extracted with CH_2Cl_2 (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, and evaporated. The crude product was dissolved in MeOH (50 mL), and then $TsOH \cdot H_2O$ (0.6 g, 3.18 mmol) was added at 0 °C. The solution was stirred for 4 h at room temperature and quenched by aqueous $NaHCO_3$. The reaction product was extracted with AcOEt (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, and evaporated. The crude product was purified by silica gel column chromatography (AcOEt/acetone = 1:1) to yield **13** (2.0 g, 5.64 mmol, 30.2%) as a colorless oil. ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 1.13 (d, $J = 6$ Hz, 3H, Me), 3.38 (s, 3H, Me), 3.45−4.02 (m, 27H); FAB HRMS (*m/z*) $[M + H]^+$ calcd for $C_{16}H_{35}O_8^+$, 355.2332; found, 355.2333.

(*S*)-Toluene-4-sulfonic Acid 2-{2-[2-(2-{2-[2-(2-Methoxy-ethoxy)-ethoxy]-ethoxy}-ethoxy)-ethoxy]-ethoxy}-1-methyl-ethyl Ester (14). Sodium hydroxide (218 mg, 5.44 mol) was dissolved in water (0.4 mL). A solution of **13** (1.5 g, 4.23 mmol) in THF (0.4 mL) was added at 0 °C. Then a solution of *p*-TsCl (887 mg, 4.65 mmol) in THF (1.0 mL) was slowly dropped into the solution. After warming to room temperature, the mixture was stirred for 7 h. Water (40 mL) was added to the reaction mixture and acidified by 6 M H_2SO_4. The reaction product was extracted with CH_2Cl_2 (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, and evaporated. The crude product was purified by silica gel column chromatography (AcOEt/acetone = 1:1) to yield **14** (1.6 g, 3.15 mmol, 74.5%) as a colorless oil. ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 1.13 (d, $J = 6$ Hz, 3H, Me), 2.45 (s, 3H, Ts), 3.38 (s, 3H, Me), 3.45−4.02 (m, 27H), 7.35 (d, $J = 8$ Hz, 2H, Ar), 7.80 (d, $J = 8$ Hz, 2H, Ar); FAB HRMS (*m/z*) $[M + H]^+$ calcd for $C_{23}H_{41}O_{10}S^+$, 209.2420; found, 509.2417.

(*S*)-*p*-Iodo-(2-{2-[2-(2-{2-[2-(2-methoxy-ethoxy)-ethoxy]-ethoxy}-ethoxy)-ethoxy]-ethoxy}-propoxy)-benzene (15). The compound **14** (0.80 g, 1.58 mmol) and *p*-iodophenol (0.41 g, 1.74 mmol) was added to a solution of K_2CO_3 (2.14 g, 15.5 mmol) in DMF (15 mL). The solution was stirred for 7 h at 70 °C. After cooling, the mixture was poured into aqueous HCl (pH = 2, 200 mL) and extracted with CH_2Cl_2 (× 2), and the organic layer was washed with brine (× 3) and dried over $MgSO_4$. The solvent was evaporated in vacuo. The crude product was purified by silica gel column chromatography (AcOEt) to yield **15** (0.96 g, 1.78 mmol, quant.) as a pale red oil. ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 1.29 (d, $J = 6$ Hz, 3H, Me), 3.38 (s, 3H, Me), 3.45−4.60 (m, 27H), 6.71 (d, $J = 9$ Hz, 2H, Ar), 7.53 (d, $J = 9$ Hz, 2H, Ar); FAB HRMS (*m/z*) $[M]^+$ calcd for $C_{22}H_{37}IO_8$, 556.1533; found, 556.1532.

(*S*)-3-Bromo-5-[4-(2-{2-[2-(2-{2-[2-(2-methoxy-ethoxy)-ethoxy]-ethoxy}-ethoxy)-ethoxy]-ethoxy}-1-methyl-ethoxy)-phenyl]-2-methyl-thiophene (16). To a solution of compound **15** (900 mg, 1.67 mmol) in dry THF (30 mL) was slowly added *n*-butyllithium hexane solution (1.6 M, 1.15 mL, 1.84 mmol) at −78 °C under an argon atomosphere. The solution was stirred for 1 h at −78 °C. After the addition of boric acid tri-*n*-butyl ester (0.672 mL, 2.51 mmol), the reaction mixture was further stirred for 1 h. The reaction was quenched by the addition of water. 2,4-Dibromo-5-methyl-thiophene (642 mg, 2.51 mmol), $Pd(PPh_3)_4$ (96.5 mg, 0.084 mmol), and aqueous Na_2CO_3 (20 w %, 30 mL) were added to the solution. The solution was refluxed for 12 h. The reaction product was extracted with AcOEt (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, filtered, and evaporated. The crude product was purified by silica gel column chromatography (AcOEt) to yield **16** (400 mg, 0.66 mmol, 39.5%) as a pale yellow oil. ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 1.32 (d, $J = 6$ Hz, 3H, Me), 2.40 (s, 3H, Me), 3.38 (s, 3H, Me), 3.52−3.80 (m, 26H), 4.57 (q, $J = 6$ Hz, 1H), 6.92 (d, $J = 9$ Hz, 2H, Ar), 6.98 (s, 1H), 7.41 (d, $J = 9$ Hz, 2H, Ar); FAB HRMS (*m/z*) $[M]^+$ calcd for $C_{27}H_{41}BrO_8S$, 604.1706; found, 604.1728.

(*S*,*S*)-1,2-Bis-[5-(4-{2-[2-(2-{2-[2-(2-{2-methoxy-ethoxy}-ethoxy)-ethoxy]-ethoxy}-ethoxy)-ethoxy]-1-methyl-ethoxy}-phenyl)-2-methyl-thiophene-3-yl]-perfluorocyclopentene ((*S*,*S*)-2a). To a solution of compound **16** (200 mg, 0.330 mmol) in dry THF (2 mL) was slowly added *n*-butyllithium hexane solution (1.6 M, 0.227 mL, 0.363 mmol) at −78 °C under an argon atomosphere. The solution was stirred for 1 h at −78 °C. After the addition of a solution of perfluorocyclopentene (0.021 mL, 0.149 mmol) in dry THF (1.2 mL), the reaction mixture was further stirred for 1 h at that temperature. The reaction was quenched by the addition of water. The reaction product was extracted with AcOEt (× 2), and the organic layer was washed with brine (× 3), dried over $MgSO_4$, filtered, and evaporated. The crude product was purified by silica gel column chromatography (AcOEt/acetone = 1:1) and separative RP-HPLC ($CH_3CN/MeOH/H_2O$ = 9:1:2) to yield **(*S*,*S*)-2a** (50 mg, 0.041 mmol, 19.5%) as a blue oil. ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 1.32 (d, $J = 6$ Hz, 6H, Me), 1.93 (s, 6H, Me), 3.38 (s, 6H, Me), 3.45−3.80 (m, 52H), 4.50−4.68 (m, 2H), 6.93 (d, $J = 9$ Hz, 4H, Ar), 7.16 (s, 2H), 7.45 (d, $J = 8$ Hz, 4H, Ar); FAB MS (*m/z*) $[M]^+$ 1224.74. Anal. Calcd for $C_{59}H_{82}F_6O_{16}S_2$: C, 57.83; H, 6.74. Found: C, 57.53; H, 6.70. UV−vis (H_2O) λ_{max} (ϵ) 295 (35 000); (AcOEt) λ_{max} (ϵ) 294 (50 000).

Corresponding Closed-Ring Isomer (*S*,*S*)-2b (Mixture of (*S*,*R*,*R*,*S*)-2b and (*S*,*S*,*S*,*S*)-2b). ^1H NMR ($CDCl_3$, TMS, 200 MHz) δ 1.33 (d, $J = 6$ Hz, 6H, Me), 2.14 (s, 6H, Me), 3.38 (s, 6H, Me), 3.45−3.80 (m, 52H), 4.50−4.68 (m, 2H), 6.57 (s, 2H), 6.94 (d, $J = 9$ Hz, 4H, Ar), 7.49 (d, $J = 9$ Hz, 4H, Ar); UV−vis (H_2O) (ϵ) 583 (16 000); (AcOEt) (ϵ) 594 (25 000).

B. Photochemical Measurements. Photoirradiation was carried out using a 500-W super-high-pressure mercury lamp or a 500-W xenon lamp. Mercury lines of 313 and 578 nm were isolated by passing the light through a combination of band-pass filters or sharp-cut filters and a monochromator. Closed-ring isomers were separated by reversed-phase HPLC ($CH_3CN/MeOH/H_2O$ = 9:1:4, flow =

1.5 mL/min), and diastereomers were separated by chiral HPLC (hexane/2-propanol/ethanol = 47:47:6, flow = 1.5 mL/min).

Quantum yields were determined by using bis(1-benzothiophen-3-yl)hexafluorocyclopentene in hexane solution as the reference.[15] The absorbance of the sample and the reference at the irradiation wavelength (313 nm) were adjusted to be the same for the cyclization quantum yield measurement. The reaction rate of the sample and the reference were measured in the same conditions and compared. For the cyclization quantum yield measurement, absorbance (A) at the absorption maximum of the closed-ring isomer was plotted against time. For the cycloreversion quantum yield measurement, $\log(10^A - 1)$ at the absorption of the irradiated wavelength was plotted against time. The measurement was carried out three times, and the value was determined by averaging.

C. DLS Measurements. Particle size distribution was measured on a Nicomp 380ZLS particle sizer equipped with a 785-nm red laser as the light source, using a fixed angle (90°). The samples were filtrated by a Millipore Millex membrane filter (0.20 μm) before measurement. The samples were kept at 30 °C during the measurement.

D. AFM Measurements. AFM images were acquired with a Digital Instruments Nanoscope III. Damage to the tip or sample was minimized by using tapping mode AFM. The aqueous solution of **1** (ca. 10^{-5} M, 10 μL) in the photostationary state was dropped on mica substrate. The sample was left about 6 h in a dark place and dried in vacuo for about 2 h at room temperature.

Acknowledgment. This work was supported by PRESTO, JST and by a Grant-in-Aid for Scientific Research (S) (No. 15105006) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Supporting Information Available: Detailed variable-temperature ^{1}H NMR spectra, the plot of the change of absorbance on cooling, and the HPLC chart for the separation of diastereomers. This material is available free of charge via the Internet at http://pubs.acs.org.

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